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# CORE FORMATION BY GIANT IMPACTS.

W. B. Tonks and H. J. Melosh. Lunar and Planetary Laboratory, University of Arizona, Tucson, Az. 85721.

Ideas about the accretion and early evolution of the Earth and the other terrestrial planets have recently undergone a number of revolutionary changes that have made much of the older work on the subject obsolete [1]. It has become clear that giant impacts were far from rare events. In the later stages of accretion any given planetary embryo is liable to be struck several times by other bodies of up to half its own diameter. Such an impact may have the ability to trigger core formation. Traditional accretion models have had great difficulty explaining the formation of a core [2]. This is because the first material to accrete should form a cold, strong inner nucleus that is difficult for later, hotter material added above it to disrupt. This difficulty is a direct consequence of the assumption that the later material is deposited in layers much thinner than the diameter of the growing planet. If, on the other hand, one admits the importance of infrequent large events that may melt an entire hemisphere, the core formation difficulty vanishes. Millimeter-size iron blebs in the melted region will rain out due to their density difference with the silicate melt. Core formation may not require the melting of an entire hemisphere of the planet. In this paper we explore the conditions under which impact induced core formation may occur. The idea of impact induced core formation is illustrated in figure 1.

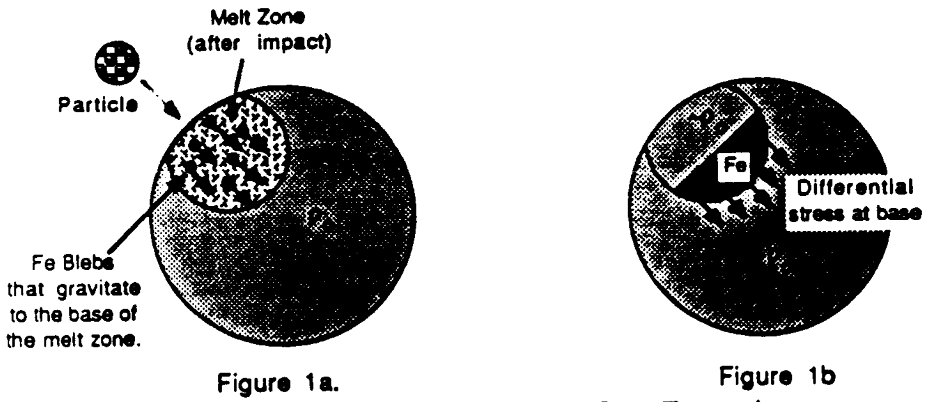


Figure 1. Impact Induced Core Formation

We envisage an approximately chondritic initial assemblage composed of chondrules, millimeter sized solid iron blebs, and matrix material. A large (compared to the size of the planet) hypervelocity impact will generate a large, approximately hemispherical region of melt. The iron blebs will also melt and rain out to the base of the melt zone (Fig. 1a). Subsequent crater modification will cause the iron to be overlain by material with approximately the same density as the original material. The iron forms a large negatively buoyant region that must be supported by the strength of the material underneath. If the stress created by the iron is too large, the iron essentially breaks through the planet and flows to the center (Fig 1b). We now explore the conditions under which core formation by this mechanism might occur.

A hypervelocity impact creates a core region of high and essentially constant pressure known as the isobaric core. The shock moves outward with diminishing pressure. As the shock passes through the material, it rapidly compresses the material to a higher pressure which then decompress adiabatically. However, irreversible pdV work has been done on the material and it is hotter than before the shock passed. If the shock pressure is sufficiently high, melting occurs. The minimum shock pressures required to melt various geological materials are around 100 GPa [3]. A value of 110 GPa, corresponding to the minimum melting shock pressure in ANEOS dunite, was used in the calculations that follow.

We estimated the effects of the growth of planetesimals in an environment governed by a cumulative mass distribution of the form, $N(>m) = Cm^{-q}$ ,where $N(>m)$ is the number of particles with mass greater than m, C is a normalizing constant, and q is the power of the distribution. Evidence of a diameter distribution of $D^{-2}$ exists from crater counts [3], the distribution of comet

nuclei sizes [4], and in numerical models of accretion. Because mass~ $D^{1/3}$, q~2/3. The actual distribution is not precisely known and might evolve over time, thus we treat it as a free parameter. We randomly generate a mass distribution over a limited mass range using the above distribution. The largest mass in the distribution is used as the bombarded planetesimal. We also input the mass of the largest planetesimal in the accretion zone of our bombarded planetesimal and the Safronov number, which determines the limits of the random velocity component. The random component is added vectorially to the escape velocity of the bombarded planetesimal. The thermal effects of the impact are estimated as follows. The radius of the isobaric core region is calculated by requiring the energy imparted to the target equals the energy (internal and particle velocity) of this region. The pressure is found using the Hugoniot equation $P = \rho_o v_p U$, where $\rho_o$ is the uncompressed density of the target, $v_p$ is the particle velocity, and U is the shock pressure. The shock pressure is modeled using the linear shock-particle velocity relationship ([3], appendix 2). We assume the material is 30% metallic iron by mass, consistent with the composition of primitive chondrites. If melting occurs, the metal melts and forms a pool at the bottom as described above. The density contrast creates a differential stress. If the average stress caused by the iron-silicate separation is greater than the yield stress, we consider the metal to have broken through the rock and a core formed. If a core did not form, another particle in the distribution is chosen. The process continues until all 1000 particles either impact, or the planetesimal is disrupted by the input of projectile kinetic energy exceeding the planetesimal's gravitational binding energy, or a core is formed. The mass of each incoming particle is added to the planetesimal's mass. Each planetesimal calculation was repeated 100 times using different random numbers to determine the probability of core formation. Figure 2 shows the results of our preliminary runs.

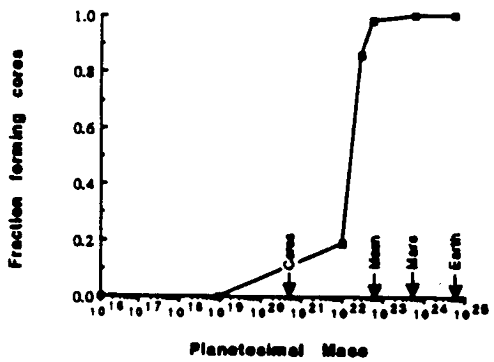


Fig. 2. Fraction of planetesimals that will form cores as a function of initial planetesimal mass. The planet grows in the calculations but does not more than double. Run condition: q = 2/3, Safronov number = 2.6, maximum material stress = 1 kbar, minimum melting shock pressure = 110 GPa, yield stress = 1 kbar, mass of largest planetesimal in the accretion zone = mass of planetesimal under investigation. Note the abrupt transition from planets that do not form cores under our run conditions to planets that do between $10^{21}$ and $10^{22}$ kg.

These runs show that the onset of impact induced core formation is quite sharp and occurs (by our criteria) in slightly smaller than lunar-sized planetesimals. Core formation requires relatively large high velocity particles. However, the planetesimal must be fairly massive to prevent disruption by such a particle. Bodies smaller than ~$10^{22}$ kg tend to be disrupted by impacts that are fast enough to induce widescale melting. Additionally, the acceleration of gravity on small objects is low; thus a small differential stress is created by the iron. It appears from this work that previously undifferentiated bodies that are lunar-sized and larger have a high probability of forming cores by large impacts. More work is needed to understand the seemingly abrupt threshold shown above and more runs are needed to check the effects of changing parameters in the calculation.

## REFERENCES

[1] Wetherill, G. W. 1990. *Ann. Rev. Earth Planet. Sci.* 18:205-256. [2] Stevenson, D. J. 1990. in *Origin of the Earth*.. Eds. H. Newsom and J. Jones, New York: Oxford University Press., pp.231-250. Stevenson, D. J. 1981. *Science*, 214:611-619. [3] Melosh, H. J. 1989. *Impact Cratering, a Geological Process*. New York: Oxford University Press; Melosh, H. J. 1990. in *Origin of the Earth*.. Eds. H. Newsom and J. Jones, New York: Oxford University Press., pp.69-83. [4] Delsemme, A. H. 1987. in *Symposium on the Diversity and Similarity of Comets*, pp. 19-30. ESA SP-278.